Three Mile Island Revisited

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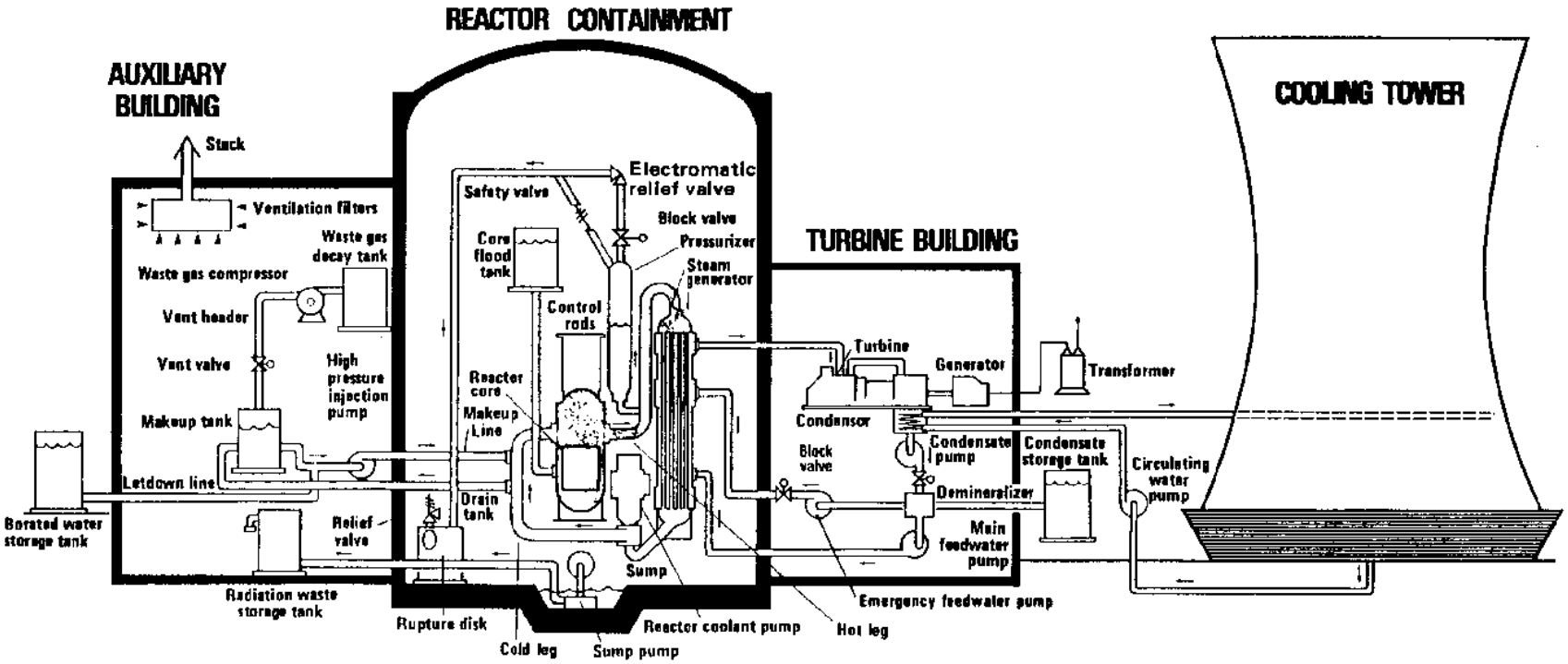
Three Mile Island Accident

- Date of accident: March 28, 1979
- Type of nuclear plant: Babcock & Wilcox 2-loop pressurized water reactor (PWR) with once-through steam generators
- Initiating event: operational upset in secondary plant (loss of condensate flow) led to trip of main feedwater pumps, which terminated feedwater flow to primary plant steam generators

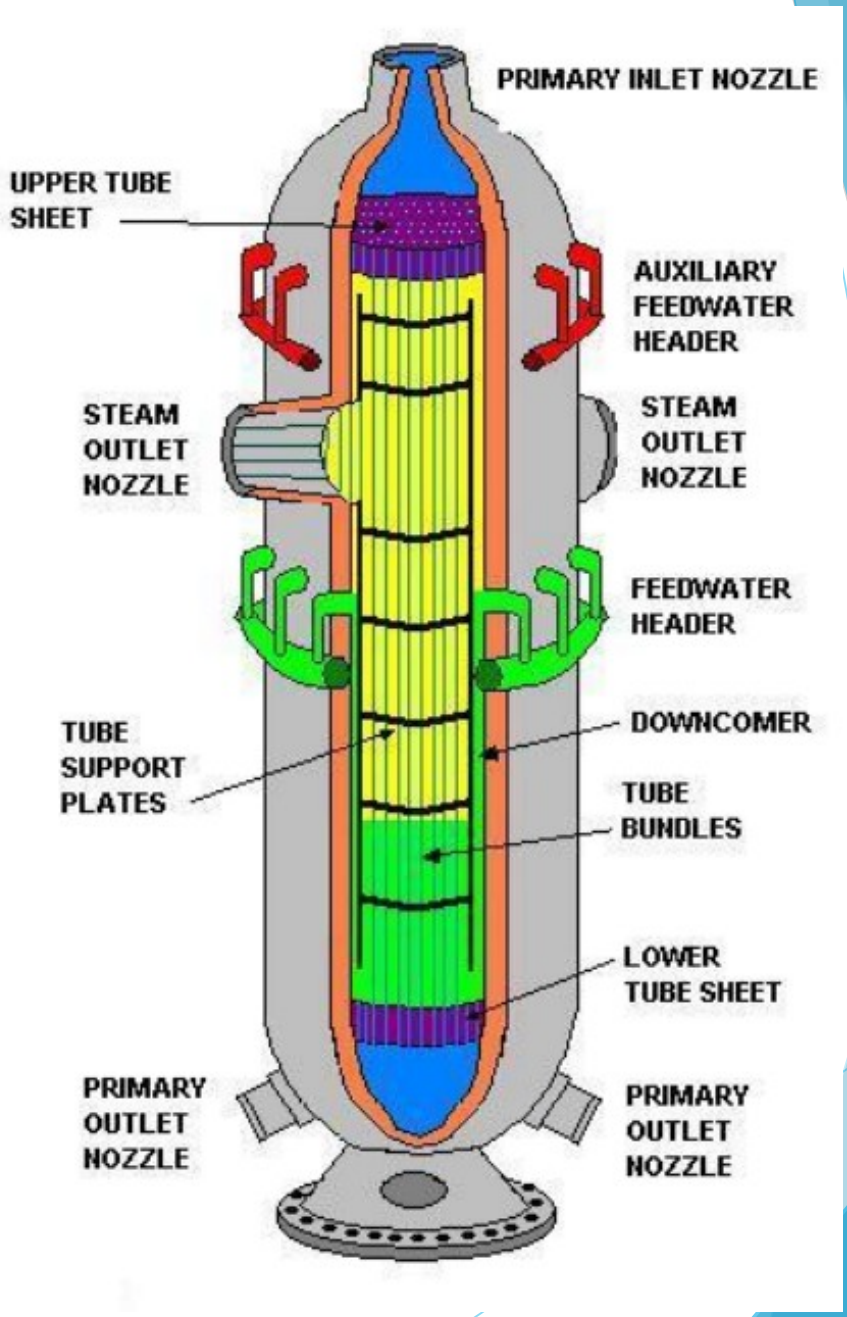
TMI Reactor Plant Schematic



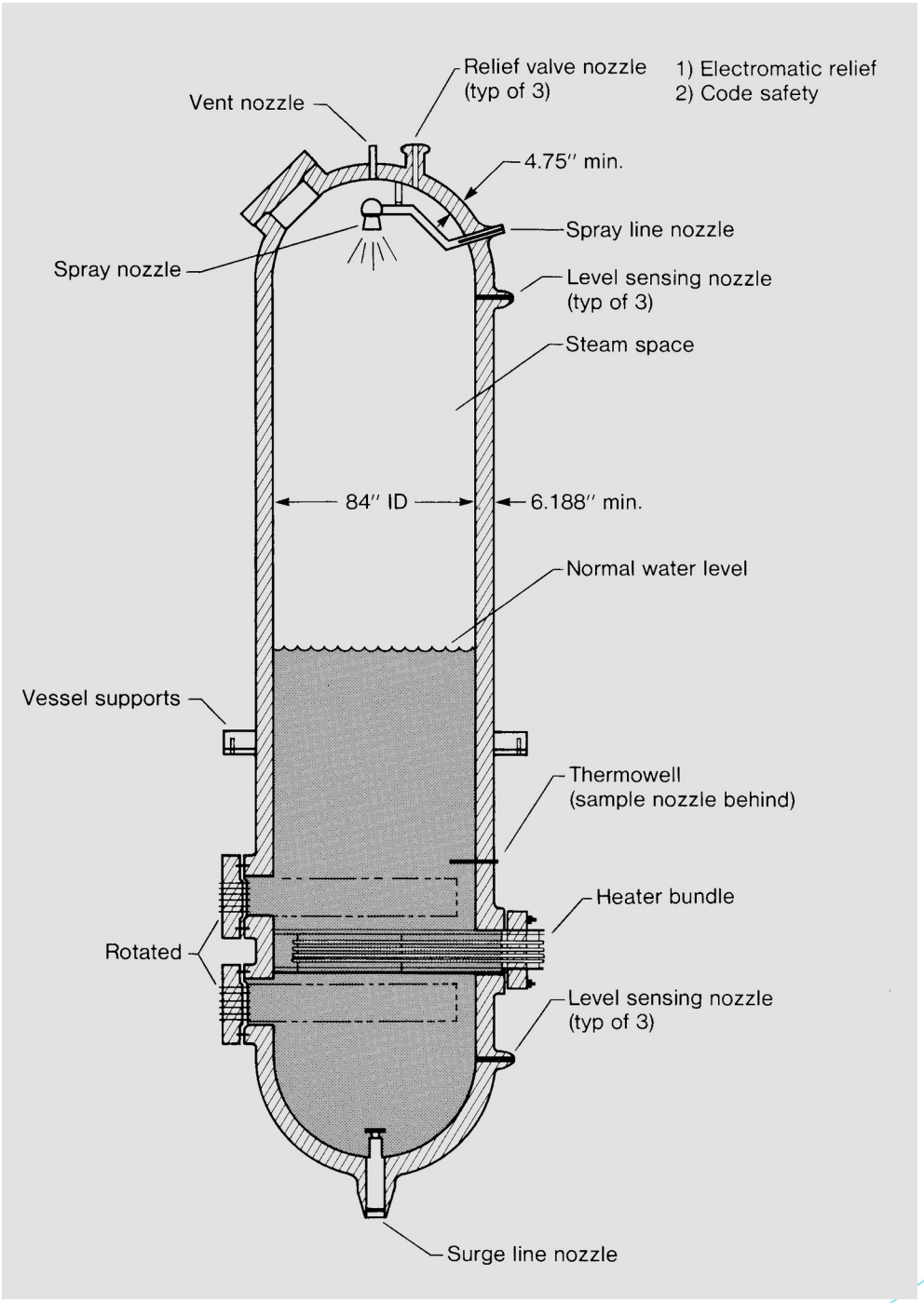
Reactor coolant system in Reactor Containment Bldg.
Main feedwater and emergency feedwater pumps in Turbine Bldg.
High pressure injection pumps in Auxiliary Bldg.

TMI Reactor Coolant System

TMI Once-through Steam Generator (OTSG)



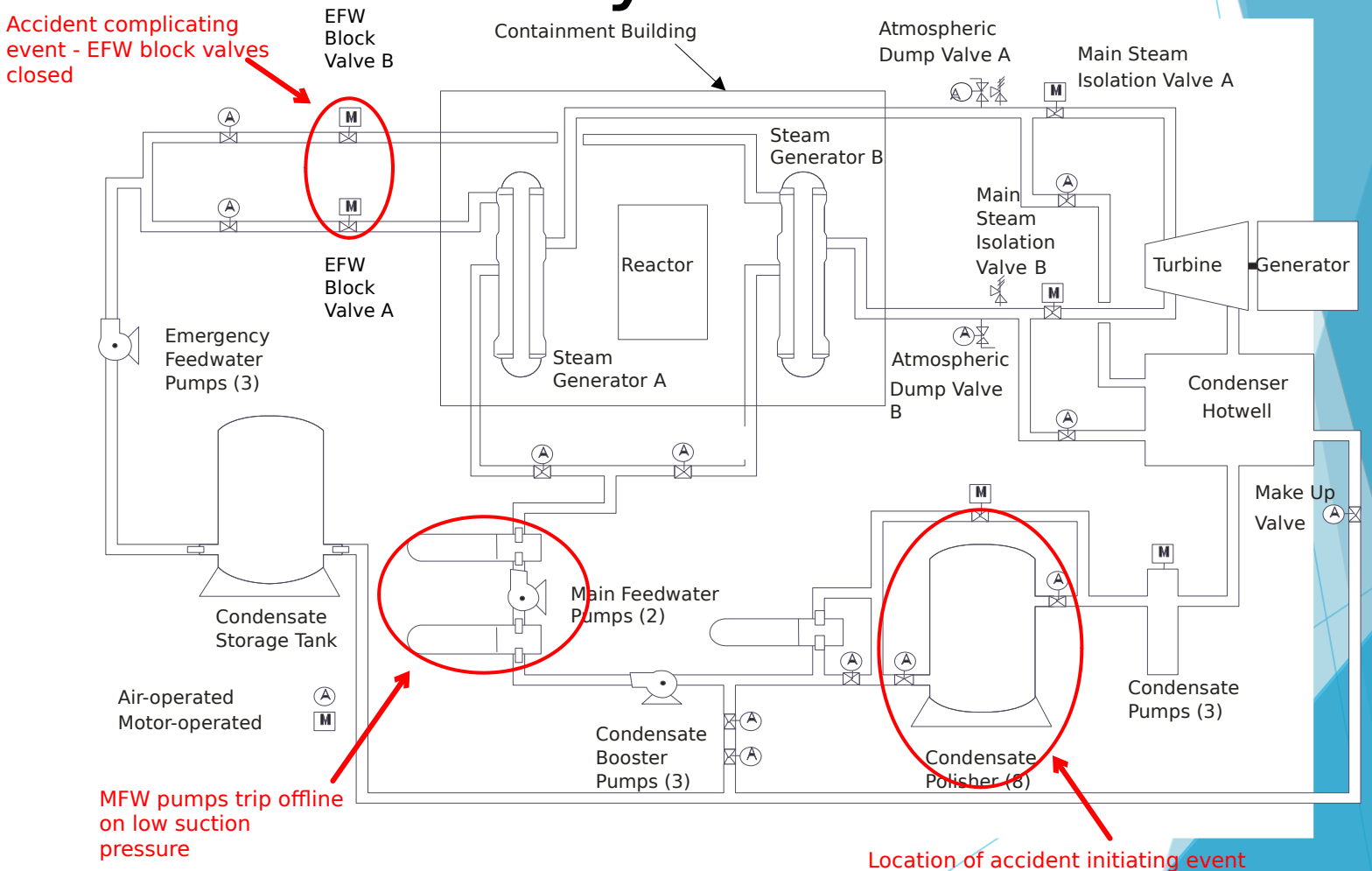
TMI Pressurizer



Reactor Coolant System Components

- Reactor coolant pump (RCP) – circulates primary coolant water from steam generator outlet to reactor vessel inlet
- Steam generator (SG) – transfers heat from high-temperature, high-pressure primary coolant water to low-temperature, low-pressure secondary coolant water to create steam for conventional steam power plant
- Pressurizer – maintains high-temperature, high-pressure steam bubble to control reactor coolant system pressure

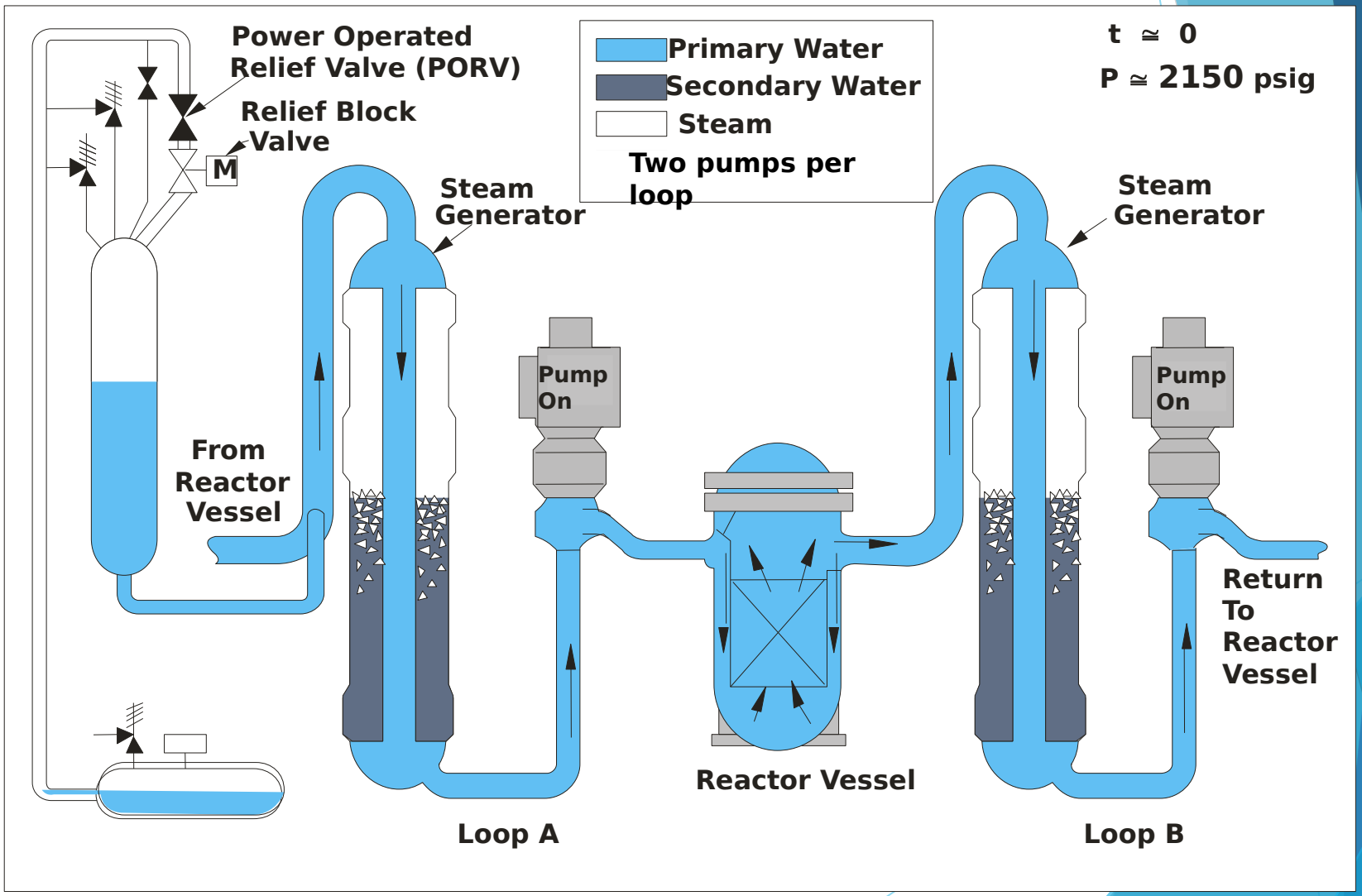
TMI Condensate & Feedwater System



Secondary Plant System Components

- Turbine-generator – converts steam energy to electricity
- Condenser – operating at partial vacuum, converts low-temperature, low-pressure steam turbine exhaust to water
- Condensate pump – pumps water from condenser hotwell to condensate polishers (demineralizers)
- Condensate polisher – removes impurities from condenser hotwell water using resin-based ion exchange to remove dissolved and suspended contaminants
- Main feedwater (MFW) pump – pumps deionized water from condensate polishers to steam generator secondary side inlet

TMI Reactor Coolant System Prior to Accident



Accident Event Sequence

- Condensate polisher (demineralizer) in secondary plant became plugged, reducing secondary coolant water flow to main feedwater (MFW) pumps
- MFW pumps tripped offline on low suction pressure
- Loss of MFW pumps caused automatic turbine trip, opening of atmospheric dump valves, and closure of main steam isolation valves
- Emergency feedwater (EFW) pumps automatically actuated to pump water from condensate storage tank to steam generator secondary side inlet
- EFW block valves, inadvertently left closed following recent EFW system maintenance, prevented secondary side cooling water from entering steam generators

Accident Event Sequence (cont.)

- Loss of feedwater supply to steam generators resulted in rise in primary coolant temperature and pressure
- Rise in primary coolant pressure caused pilot-operated relief valve (PORV) on pressurizer to open at 3 seconds
- Reactor control rods automatically inserted on high primary system pressure at 8 seconds, terminating fission reaction in reactor fuel
- Steam from pressurizer directed to quench tank in reactor containment building as primary coolant pressure began to decrease

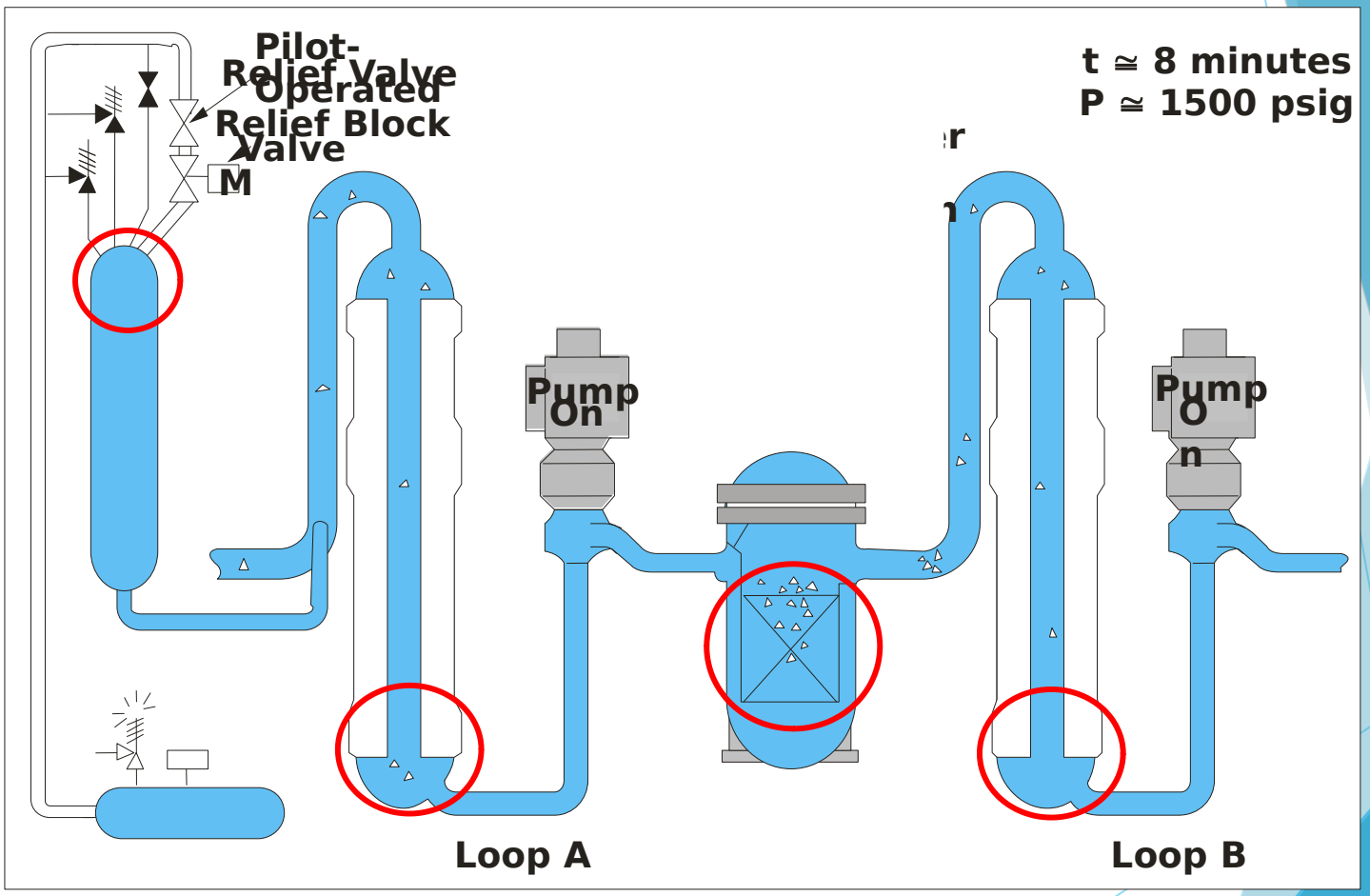
Accident Event Sequence (cont.)

- About 2 minutes into accident
  - steam generators boiled dry
  - emergency core-cooling system high-pressure injection (HPI) pumps automatically started pumping water into primary system from borated water storage tank as reactor coolant system pressure continued to decrease
- Observing rapid rise in pressurizer water level at about 4.5 minutes into accident, control room operator overrode one HPI pump, then the other
- At about 5.5 minutes water in reactor core began to boil

Accident Event Sequence (cont.)

- PORV failed to re-close when primary system pressure dropped below relief valve set-point, resulting in loss-of-coolant accident (LOCA) condition
- About 6 minutes into accident steam bubble in pressurizer lost

TMI Reactor Coolant System 8 minutes into Accident

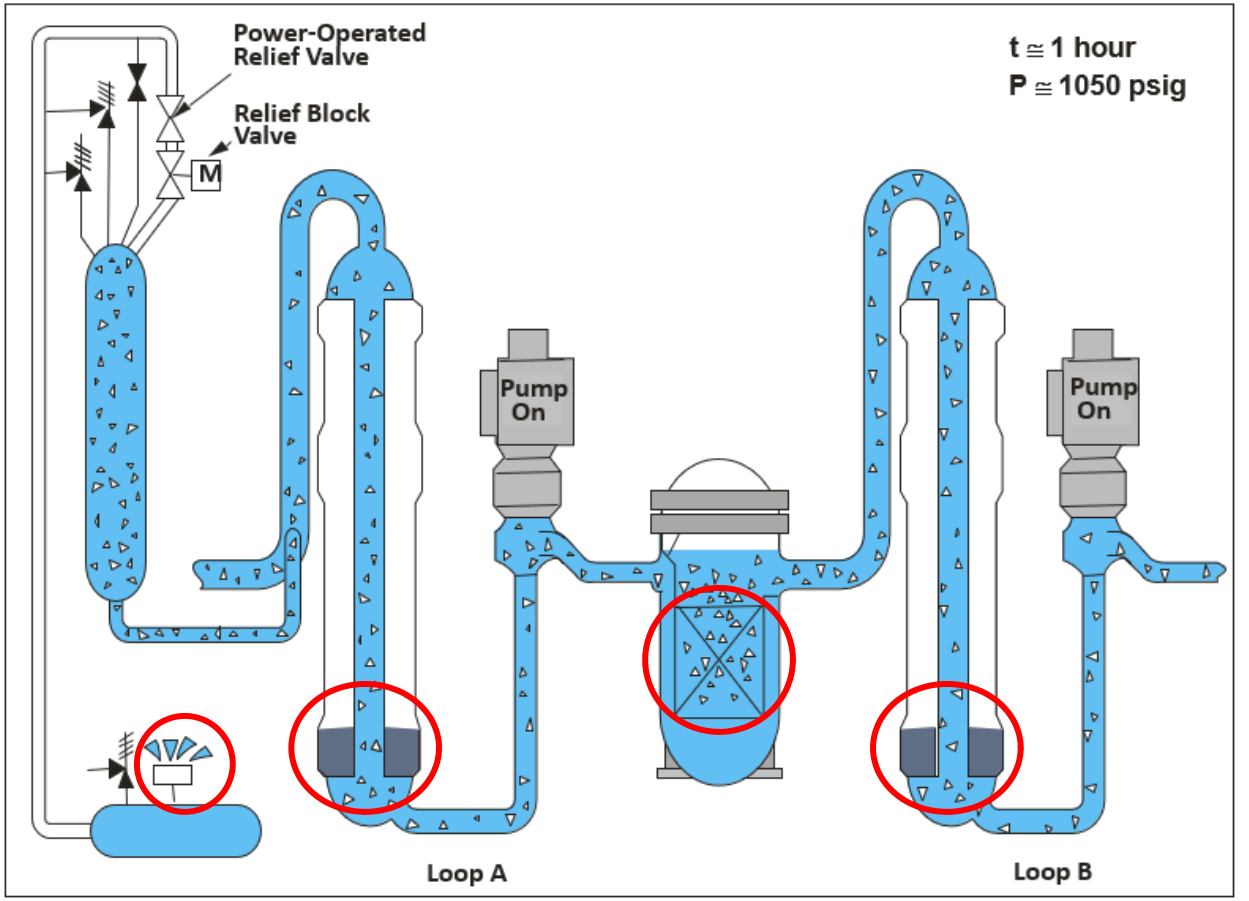


Pressurizer “solid,” steam generators dried out, high-pressure injection stopped, steam bubbles forming in core region

Accident Event Sequence (cont.)

- At about 8 minutes after accident began, control room staff discovered closed emergency feedwater isolation valves; opening valves restored feedwater flow to steam generators
- Reactor coolant continued to be released from primary system through stuck-open PORV
- At 15 minutes into accident quench tank rupture disc burst, releasing primary coolant into containment building

Reactor Coolant System
1 Hour into Accident

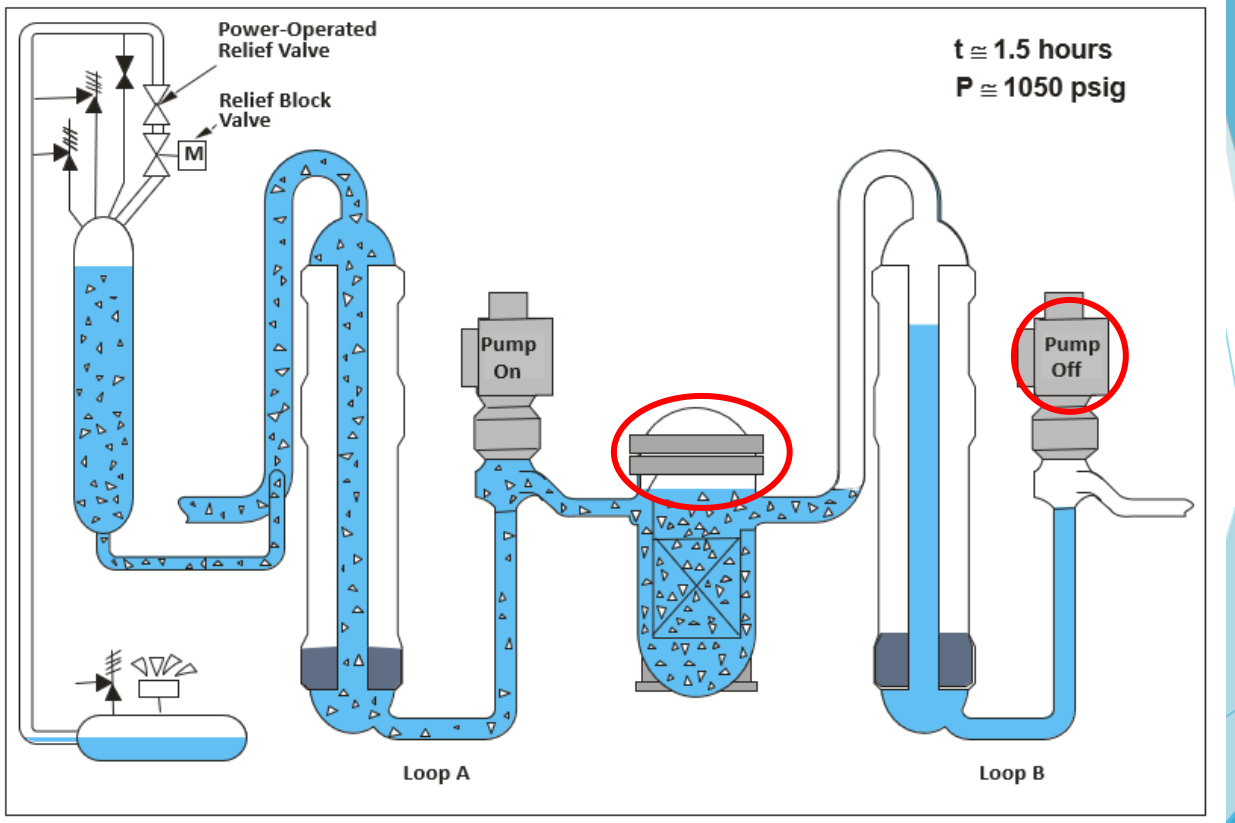


Quench tank rupture disk burst, boiling occurring in reactor core, feedwater flow restored to steam generators

Accident Event Sequence (cont.)

- At one hour and fifteen minutes into accident two reactor coolant pumps (RCP) in cooling Loop B shut down in response to indications of low system pressure, high vibration, and low coolant flow
- Voids from boiling in reactor core begin collecting in reactor vessel head

Reactor Coolant System 1.5 Hours into Accident

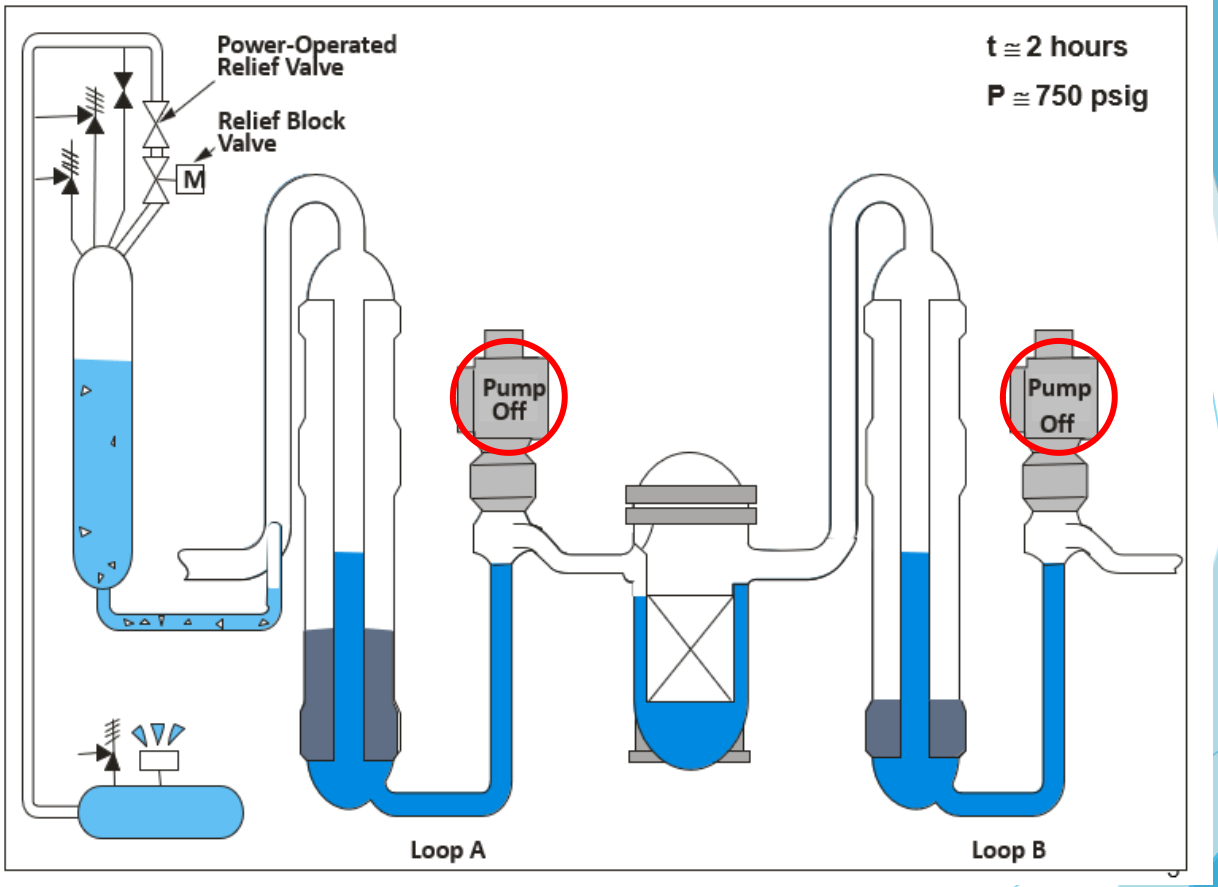


Loop B reactor coolant pumps shut down; steam bubbles begin collecting in reactor pressure vessel head

Accident Event Sequence (cont.)

- At one hour and forty minutes into accident two RCPs in cooling Loop A shut down
- Loss of forced circulation cooling in reactor core resulted in overheating of fuel elements

Reactor Coolant System 2 Hours into Accident

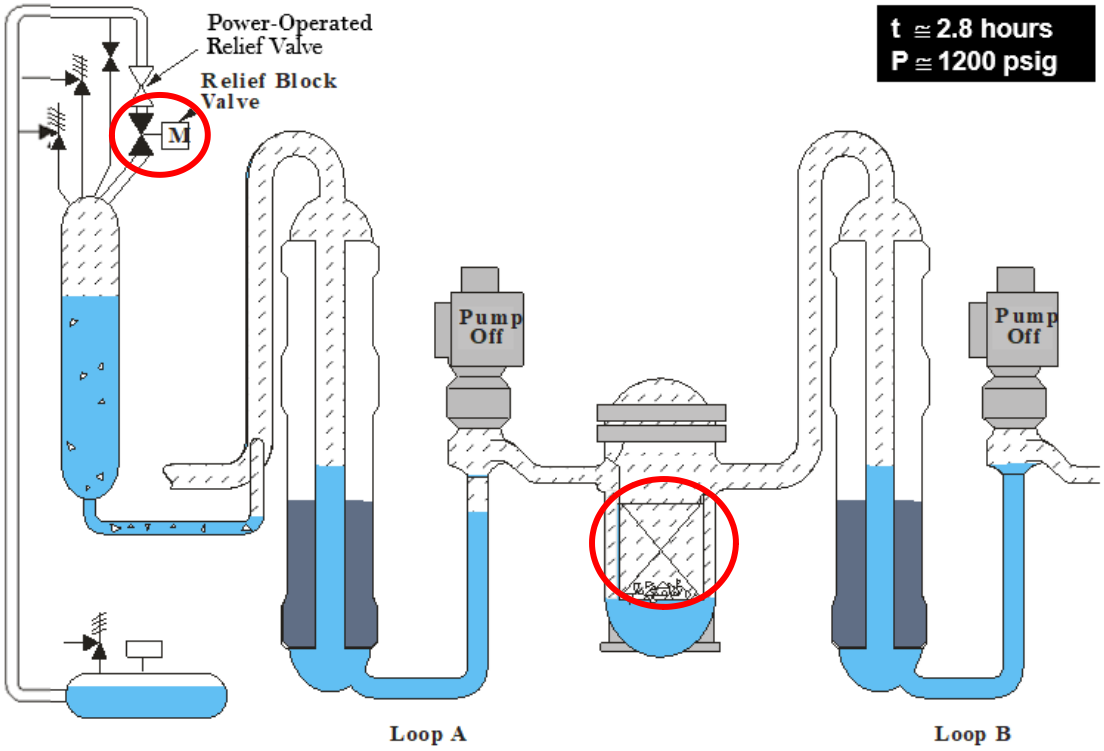


Loop A reactor coolant pumps shut down

Accident Event Sequence (cont.)

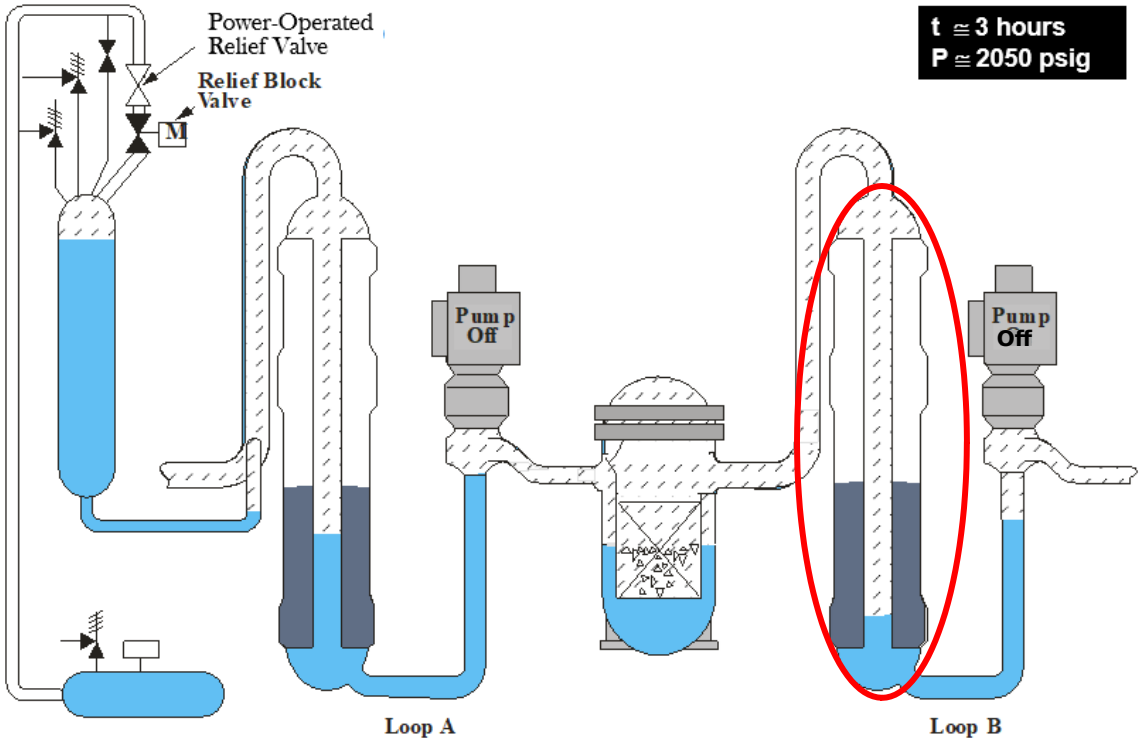
- Stuck-open PORV discovered at 2 hours and 20 minutes into accident
- PORV block valve closed, terminating loss of reactor coolant
- Emergency core cooling HPI re-initiated with one pump at 2.5 hours for 10 minutes
- Overheating of fuel elements ruptures fuel rod cladding
- At 3 hours into accident, Loop B steam generator isolated when primary-to-secondary leaks detected

Reactor Coolant System 2.8 Hours into Accident



PORV block valve closed, overheating of fuel bursts fuel rod cladding

Reactor Coolant System 3 Hours into Accident

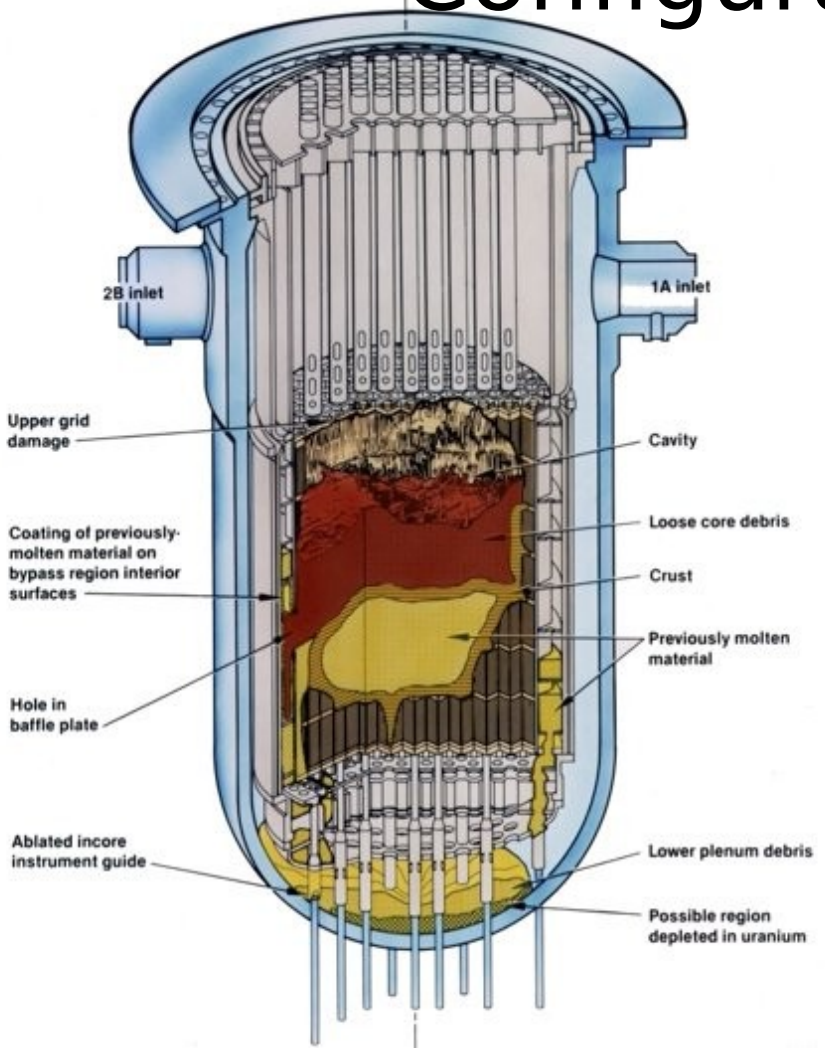


Cooling Loop B steam generator isolated

Accident Event Sequence (cont.)

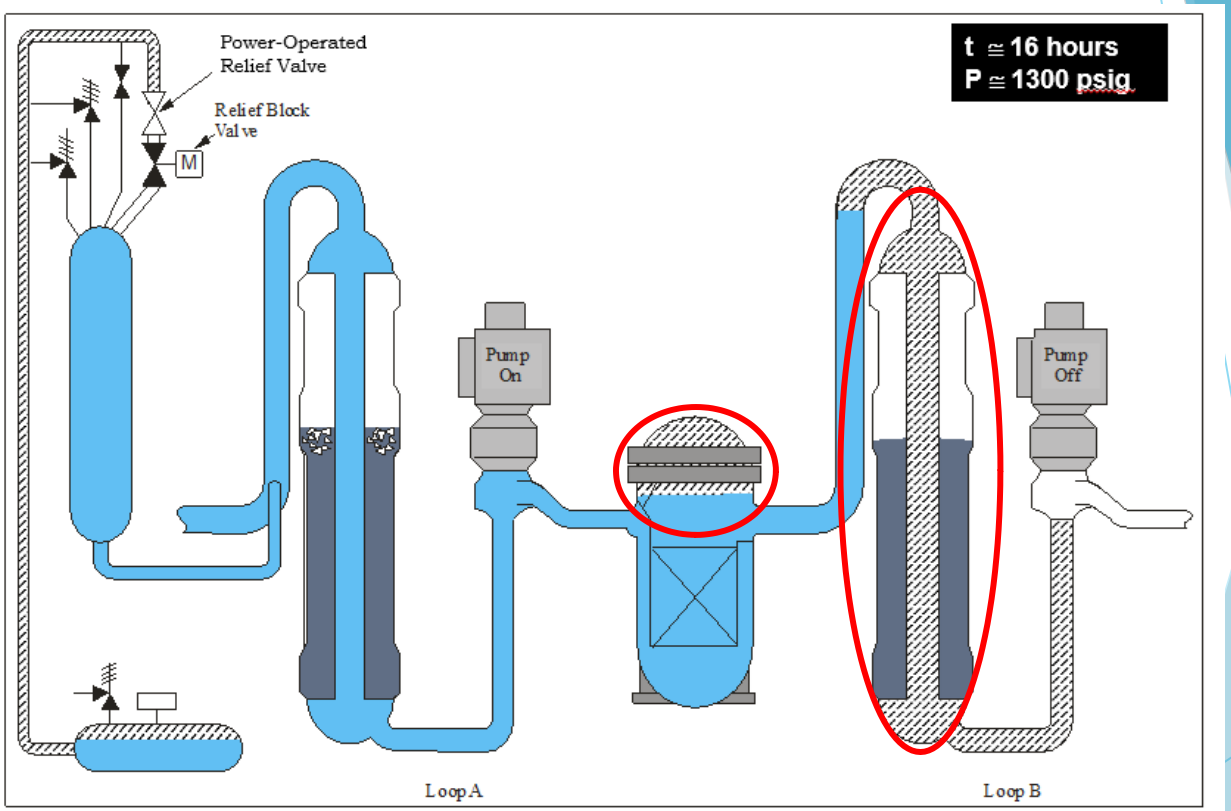
- At 2 hours and 45 minutes, attempts to restart RCPs in cooling Loop A failed
- One RCP in cooling Loop B restarted at 2 hours and 55 minutes and stopped 20 minutes later
- Emergency core cooling HPI re-initiated at 3 hours and 20 minutes
- About 4 hours into accident, upper part of reactor core melts and slumps to bottom of reactor pressure vessel
- Coolable core geometry established with emergency core cooling system at about 5 hours, terminating accident

Reactor Core End-State Configuration



- Upper portion of reactor core melted
- Melted fuel and core structural debris collected in bottom of reactor pressure vessel
- Pressure vessel incurred no damage

Reactor Coolant System
16 Hours After Accident Initiation

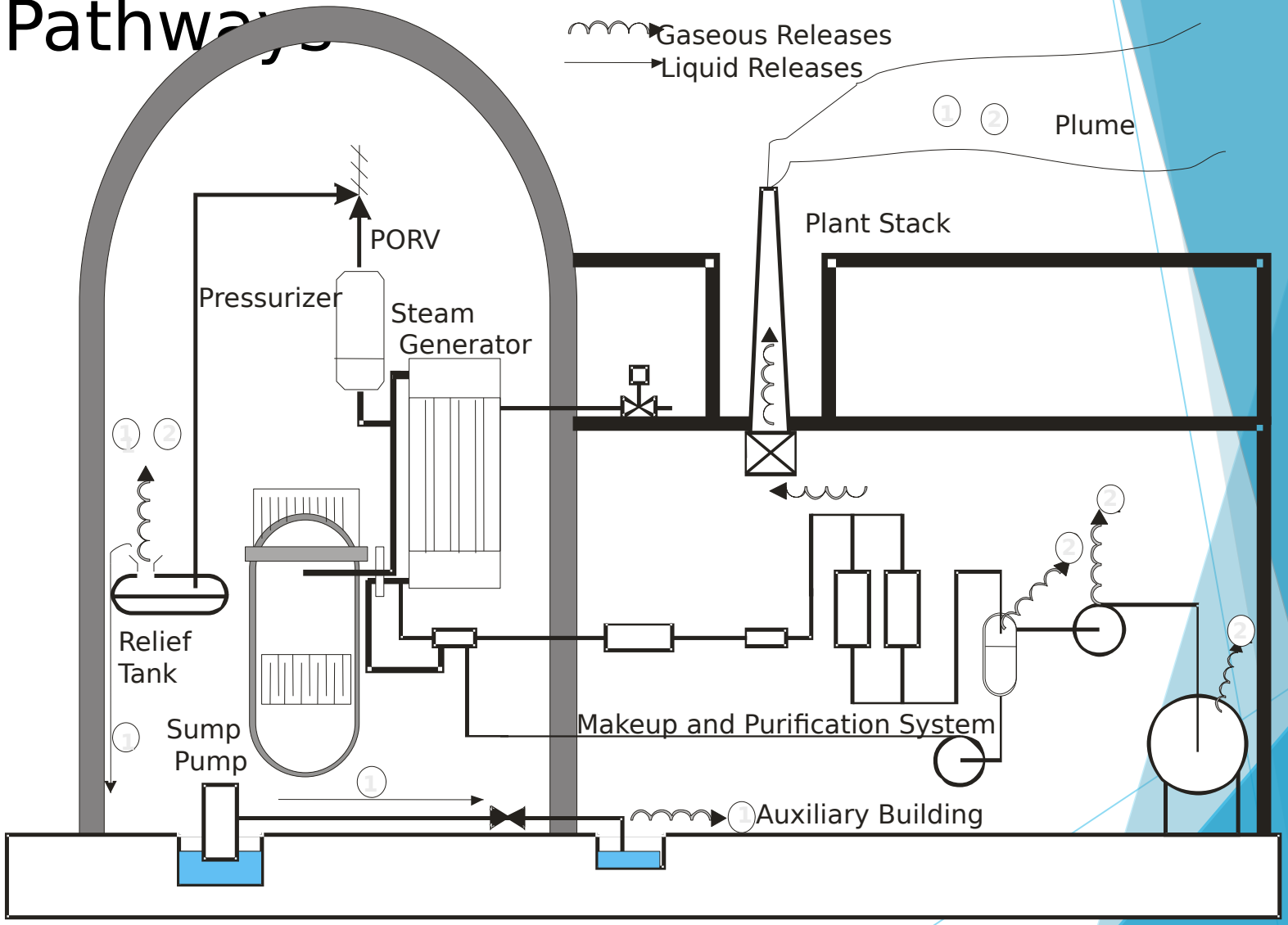


Post-accident reactor coolant system status; Loop B steam generator isolated, steam bubble in reactor pressure vessel head

TMI Accident Radiological Consequences

- Noble gases, primarily krypton-85, released to atmosphere by controlled venting spread out over approximately one month
- Exposure to nearest known offsite individual believed to be no more than 37 mrem (0.37 mSv) from noble gas releases, or about one-tenth of average American's annual exposure from natural background radiation
- Semi-volatile radionuclides like iodine became immobilized by plating out on primary coolant system and containment building surfaces

TMI Accident Radiation Release Pathways



Noble gas leakage from makeup and purification system and from auxiliary building sump constituted only radiation release from plant

Radiological Consequences (cont.)

- Nearly 2 million liters of contaminated water in auxiliary building processed through EPICOR-II (commercial ion-exchange unit designed to handle routine radioactive wastes from reactor operation)
- More than 2 million liters of highly contaminated water in containment building and another half million liters in reactor coolant system processed through specially designed submerged demineralizer system
- Radioactive ion-exchange material shipped offsite for disposal

Radiological Consequences (cont.)

- Tritiated water remaining in residual processed water initially stored onsite in two large tanks
- Disposal to Susquehanna River, permissible under federal standards, prevented by legal injunction
- Final disposal of tritiated water by evaporation allowed after protracted litigation

Post-Accident Assessment – Prescriptive Operating Procedures

- Because reactor operators trained in strict adherence to prescriptive operating procedures, primary focus early in accident was on increasing pressurizer water level instead of decreasing reactor coolant pressure
- If primary coolant system pressure had been criterion for determining continued operation of high-pressure injection system, steam bubble would not have formed in reactor vessel head and fuel melting would not have occurred

Post-Accident Assessment – Inexplicable Human Error

Effect on accident progression of EFW block valves mistakenly left closed following system maintenance subject to dispute

- Babcock & Wilcox contended impact of 8-minute absence of feedwater to SGs on accident progression was significant
- Kemeny Report[1] stated 8-minute delay in establishing EFW flow did not directly affect outcome of accident, but served as diversion of operator attention
- Rogovin Report[2] stated 8-minute loss of EFW had no significant effect on outcome of accident, but added to confusion that distracted operators from understanding cause of anomalous instrument readings

1. President's Commission on the Accident at Three Mile Island, 1979
2. NRC Special Inquiry Group or Rogovin Committee, 1980

Post-Accident Assessment – Pressurizer Water Level

Loss of steam bubble in pressurizer caused operators to believe that reactor core was covered with water

- Emergency core cooling high-pressure injection pumps throttled to prevent over-pressurizing reactor coolant system
- Persistent high pressurizer water level resulted from obscure thermal-hydraulic phenomenon called “countercurrent flooding,” whereby upward flow of steam rising from reactor core through pressurizer inlet piping suspended water in upper part of pressurizer
- 1978 TVA engineer’s analysis of LOCAs in Babcock & Wilcox PWRs concluded that pressurizer water level not reliable indicator of reactor coolant system conditions and should not dictate operator actions
  - TVA, NRC, and B&W share responsibility for downplaying (or ignoring) significance of analysis

Post-Accident Assessment – Mayhem in the Control Room

Ambiguous control room indications and reactor system conditions complicated task of mitigating accident while still adhering to operating procedures

- Control room alarm boards “lit up like a Christmas tree” (more than 100 alarms activated)
- Many instruments gave unexpected readings
- Computer alarm log printed one line every 4 seconds

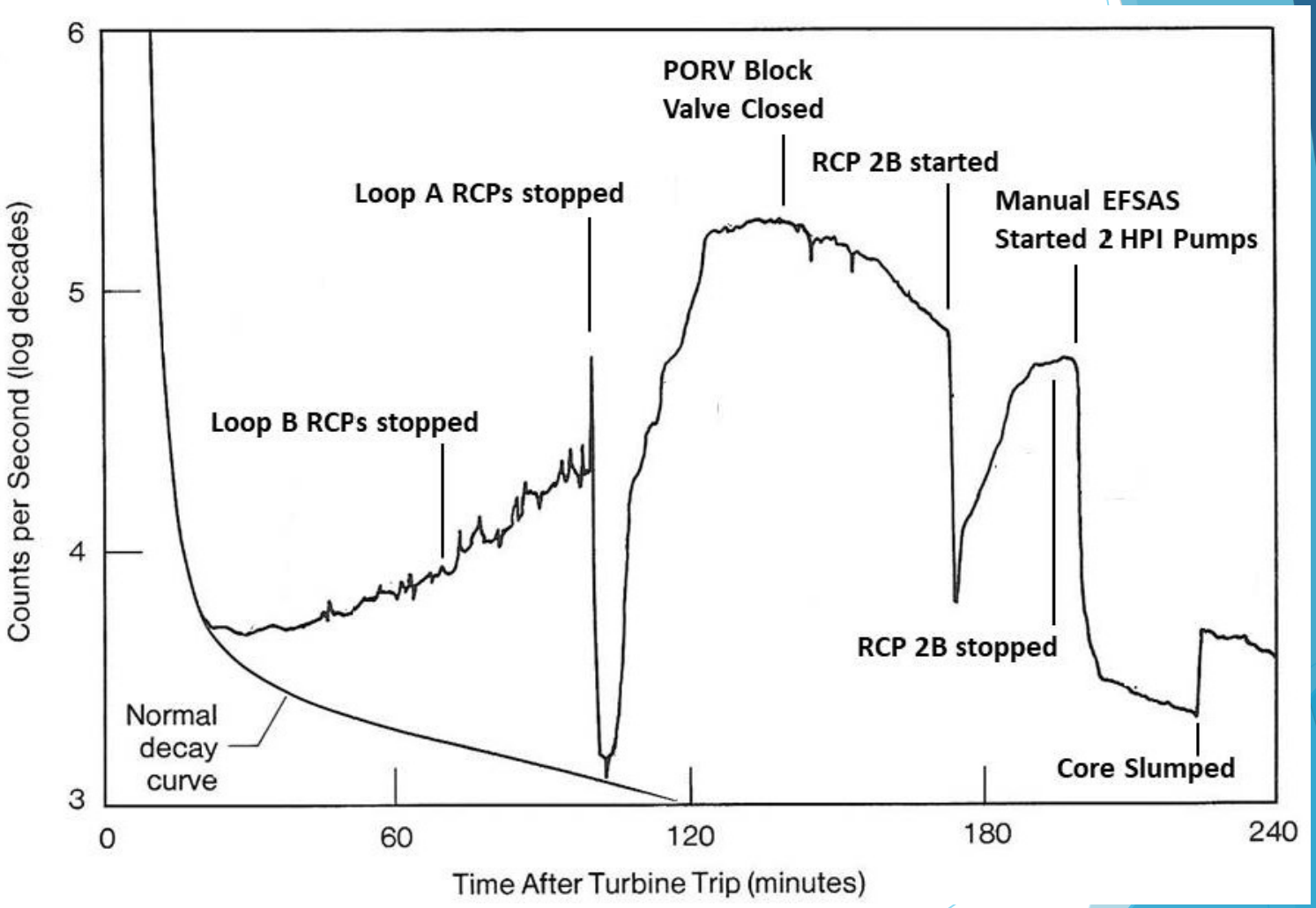
TMI-2 Control Room

Alarm boards in upper portions of control room panels

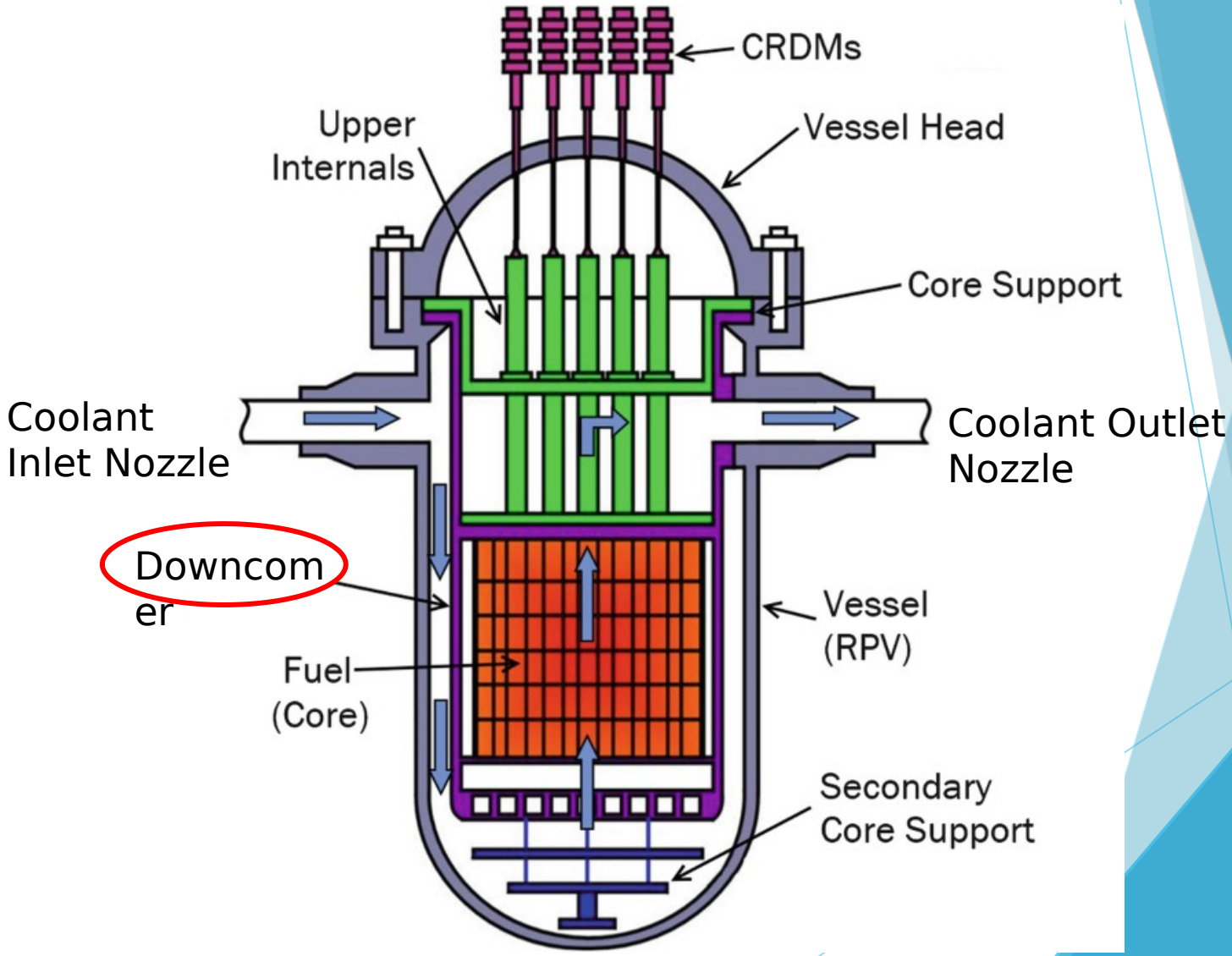
Post-Accident Assessment – Unexpected Instrument Readings

- Ex-core source range neutron monitor (SRM) count rate followed normal post-reactor-trip decay curve for first 20 minutes following turbine trip before increasing unexpectedly for next 80 minutes (next slide)
- Rise in SRM count rate interpreted by operators, engineers, and plant management as potential return to criticality
  - Increasing count rate resulted from reduced attenuation of neutron flux due to increasing steam fraction of reactor coolant in reactor vessel downcomer (see Reactor Pressure Vessel slide)
  - When Loop A RCPs stopped at around 100 minutes, water and steam phases in reactor coolant separated, increasing density of coolant in downcomer, resulting in more neutron flux attenuation, causing SRM count rate to drop

TMI-2 Unexpected SRM Signal



TMI Reactor Pressure Vessel



Post-Accident Assessment – Unexpected Instrument Readings (cont.)

- SRM count rate anomaly (cont.)
  - As boiling in core continued, water level in downcomer decreased, lowering neutron attenuation, causing count rate to rise again
  - SRM count rate continued to reflect changes in neutron flux attenuation by downcomer coolant for remainder of accident
  - Nothing in operator training or procedures to properly interpret unexpected SRM indications

Post-Accident Assessment – the Good, the Bad, and the Ugly

The Good

- Accident was successful, but very expensive, “safety experiment”* desired by nuclear industry for long time
  - Despite fuel melting, debris “froze” quickly upon contact with bottom of reactor vessel
  - Bottom of reactor vessel incurred no damage
- Unanticipated plate-out of semi-volatile radionuclides on containment building surfaces made them unavailable for release to environment (behavior of iodine and cesium less threatening than expected)
- Reactor containment building, ultimate fission product retention barrier, even accommodated hydrogen deflagration event without incurring damage

* Characterization of accident by GPU Nuclear Executive Vice-President E.E. Kintner

Post-Accident Assessment – the Good, the Bad, and the Ugly

The Good (cont.)

- Post-accident nuclear industry changes
  - Conversion from event-based to symptom-based operating procedures
  - Enhanced plant monitoring and maintenance
  - Control room redesign
  - Upgraded operator training
  - Renewed focus on human factors in reactor safety analyses
  - Enhanced plant risk assessments
  - Improved industry communications, especially for abnormal event reporting
  - Establishment of Nuclear Safety Analysis Center (NSAC) and Institute of Nuclear Power Operations (INPO)

Post-Accident Assessment – the Good, the Bad, and the Ugly (cont.)

The Bad

- Accident severely damaged public perception of nuclear power
- Local emergency sirens, coupled with radio and television coverage, magnified perceptions of danger
- Accident communicated by media as unmitigated disaster, based on speculation from “experts” and anti-nuclear activists alike
  - Conflicting information and technical complexities led to some sensationalism and misrepresentation of true risks, including predictions of radiation-induced cancer mortality for surrounding population

Post-Accident Assessment – the Good, the Bad, and the Ugly (cont.)

The Bad (cont.)

- One excess cancer fatality predicted for population of 2 million persons within 50-mile radius of plant
  - Collective dose concept used to estimate average individual dose of 1.5 mrem for “exposed” population of 2 million persons
  - Long-term cancer fatality risk estimate from 1.5 mrem dose based on BEIR 1972 Report with no threshold dose (linear no-threshold dose response model)
  - 1.5 mrem within variation of U.S. average annual dose from natural background radiation, which harms no one

Post-Accident Assessment – the Good, the Bad, and the Ugly (cont.)

The Ugly

- Two days after accident, Pennsylvania Governor “encouraged” pregnant women and children within 5 miles of plant to evacuate until further notice, producing unwarranted public fear
- Pennsylvania state emergency management agency drew up evacuation plans for 20-mile radius from plant affecting 6 counties and 650,000 people, increasing public fear
- While no evacuation ordered, panic ensued and schools closed
- Unscientific NRC speculation of hydrogen explosion that could destroy reactor vessel only exacerbated public fears

Post-Accident Assessment – the Good, the Bad, and the Ugly (cont.)

The Ugly (cont.)

- Error in NRC accident risk calculations (revealed by Kemeny Report) never communicated to public
- Utility ratepayers still suffer from damage to nuclear industry by anti-nuclear forces and hostile media
  - 51 U.S. nuclear power plants cancelled between 1980 and 1984
  - No new nuclear power plants authorized for construction between 1979 and 2012
  - Vogtle Units 3 & 4 only nuclear plants constructed since 2012
  - As of May 2025, only one advanced power reactor construction permit application in NRC review process

Post-Accident Assessment – the Good, the Bad, and the Ugly (cont.)

The Ugly (cont.)

- Some 300 initial claims by entities within 25-mile radius of plant for health effects, property damage, and economic loss paid by insurance without legal challenge
- Stimulated by ease of recovery of “damages” from initial claims, many additional lawsuits filed
  - Out-of-court settlements for personal injury claims made for 70 children and for estates of 4 men who died since accident
  - More than 2100 lawsuits were still pending more than 10 years after accident

TMI-2 Current Plant Status

- Fuel removed from reactor vessel, plant cleaned up, decontaminated, and placed in post-defueling monitored storage
- Unit 2 to be decommissioned with Unit 1 at end of Unit 1’s useful lifetime (Unit 1 shut down in September of 2020, but now being considered for restart to power Microsoft AI data center)

TMI – Pre-Accident

TMI – Post-Accident

References

- NUREG/CR-1250, *Report of the President's Commission on the Accident at Three Mile Island,* J.G. Kemeny, chairman (Oct. 30, 1979)
- *Three Mile Island: A Report to the Commissioners and to the Public*, M. Rogovin, director of Special Inquiry Group, U.S. Nuclear Regulatory Commission (Jan. 1980)
- J.S. Walker, *Three Mile Island: A Nuclear Crisis in Historical Perspective,* University of California Press (2004)
- R.E. Henry, *TMI-2: An Event in Accident Management for Light-Water- Moderated Reactors,* American Nuclear Society (2011)
- *Three Mile Island:* Burchill, W.E., Insights from the Three Mile Island accident, Part 1: The accident, *Nuclear News*, May 2019